A METHOD FOR ESTIMATING REQUIRED THICKNESSES OF FLEXIBLE BASE

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SYNOPSIS

This method is based on the tests reported by Spangler and Ustrud.[1]

The 3000-lb. load, 50-psi. inflation pressure, and 60.4-sq. in. contact area were selected since the tests were extended to include depths of base up to 10 in.

The proposed method takes into account:

1. The very high stress in the center of the loaded area. This concentration factor is due to the peculiar functioning of the pneumatic tire itself. It cannot be duplicated by metal plates.
2. The cone of load distribution.
3. The shearing value of the subgrade as determined by the California bearing ratio.

On examining the pressure graphs shown in Spangler and Ustrud's paper, attention is immediately drawn to the concentration of pressure indicated directly beneath the tire contact. That this concentration does in fact exist is a matter of common observation, but these graphs are the first experimental record of this fact to this writer's knowledge. They explain clearly the grooving action of the pneumatic tire.

As nearly as can be measured on the graphs, the high pressure area extends about an inch each way from center of load. Assuming, for simplicity, the shape of this high compression area to be circular, then the radius is one inch and the area is 3.14 sq. in. For practical purposes this is 5 percent of the gross contact area. The authors have rounded off the unit pressures in this small area. They show the unit pressure as 67 psi. It is the writer's belief that at the instant of contact of a moving tire with the base of paved surface the pressure is much greater, and not less than $W \div 5$ percent gross contact area. For $W = 3000$ lb. the unit pressure would be $3000 \div 3.02$ or approximately 1000 psi. This is a fleeting load. Almost instantaneously the pneumatic tire adjusts itself, the contact area increases and the unit pressure on the base drops. Nevertheless the small area of concentrated stress is there, whether you see it or not. It is this circle of maximum compression which the writer uses as the top of the cone of load dispersion in Figure 2. The area of this circle is assumed to be 5 percent of the gross contact area.

ANGLE OF LOAD SPREAD

The angle of load spread, or cone of distribution, is determined as follows: From the graphs (Figures 13, 14, and 15, Pages 249 and 250, Reference 1) the unit pressures are given for each thickness of base course tested. They are shown in Table 1. The wheel load W divided by the unit pressure defines the area over which the load has spread.

From Table 1 it is seen that the area of unit pressure A expands at a fairly uniform rate. In Figure 1 the radii of the successive areas are plotted. The angle of dispersion is closely 24 deg. 54 min. and its natural tangent is 0.464.

In Figure 2 the mechanics of the method are assembled in working order. In this frustrum of a cone the top is the area of concentrated stress, equal to 5 percent of the gross tire contact area. The radius of this small circle is a.

From the perimeter of this circle of concentrated pressure the load disperses downward through an angle of 24 deg. 54 min. to the subgrade. The radius of the circle over which the load is distributed at any depth d is $(a + 0.464d)$ and the area is $(a + 0.464d)^2\pi$.

The unit stress, S, on the subgrade due to the load W is $S = \dfrac{W}{(0.454\,d + a)^2\pi}$.

DETERMINATION OF VALUES FOR S

The writer uses the California bearing ratio to determine the subgrade resistance to load.

[1] Reference 1. Spangler and Ustrud, *Proceedings*, Highway Research Board, Vol. 20, pp. 235–257 (1940).

For small laboratories with limited funds available for research this method is dictated by necessity. However, the writer prefers this method not only for its simplicity but also for the additional information it yields aside from its measure of the resistance to shear.

TABLE 1

Thickness of Base Course	Unit Pressure	Pressure Area[a] A	Radius of Press Area[b]
in.	*psi.*	*sq in.*	*in.*
3	67	45	3.8
4	59	51	4.0
5	51	59	4.3
6	37	81	5.1
8	25	120	6.2
10	19	158	7.1

[a] $A = \dfrac{W\ (= 3000)}{\text{Unit Pressure}}$.

[b] $r = \sqrt{\dfrac{A}{\pi}}$.

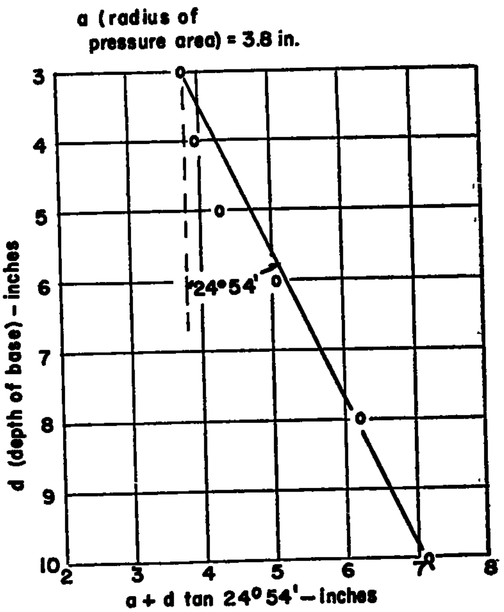

Figure 1. Method of Determining Load Spread (See Table 1)

This test measures volume change; it will bring out the effect of poor or good gradation in fine sands; it indicates within practical limits the effects of plastic fractions.

It has been objected that thicknesses of base and surface indicated by the CBR are, unduly conservative. It may be observed that it is rarely possible to be too conservative in the matter of providing a lasting foundation; the cost of repairing a poor one will in most cases far outrun the first cost of a good one.

For those who consider the indications of the CBR test excessive, it is suggested that they may arrive at a lesser moisture content at the time of test by careful observation of the existing moisture content in subgrades under flexible surfaces now in use in the immediate vicinity of the proposed work. The term "immediate vicinity" is used advisedly. Some unexpectedly adverse results have been met with through the proneness of designers to assume that soils of similar gradation react under load in like manner. There is much we do not know about soil behavior; but of one thing we are reasonably certain; gather

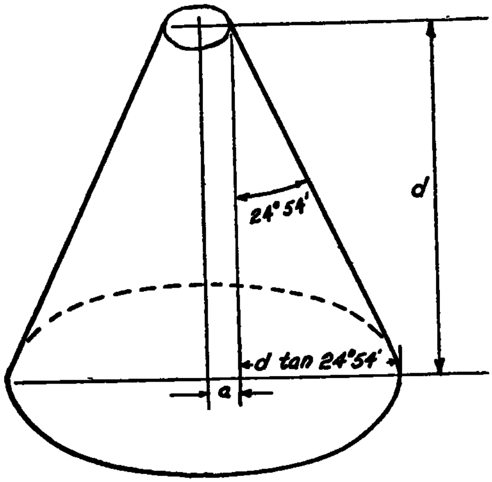

Figure 2. Cone of Load Distribution

Top of frustrum is circle of maximum pressure with radius a
Area of base $= \pi(d \tan 24°54' + a)^2$
Area of circle of max. pressure equals 5 percent of gross tire contact area A
Radius of circle of max. pressure,

$$a = \sqrt{\frac{0.05A}{\pi}} = 0.126\sqrt{A}$$

$$s = \frac{W}{\pi(d \tan 24°54' + a)^2}$$

where s = subgrade resistance in psi. from CBR test at 0.1-in. penetration
W = total wheel load in pounds
d = thickness of base course in inches

and

$$d = 1.216\sqrt{\frac{W}{s}} - 0.272\sqrt{A}$$

your data just as close to the proposed work as possible.

If, now, the engineer can establish with reasonable certainty that the moisture content of the subgrade under existing flexible surfaces will not rise above a given percentage, he may use that as the moisture content of his samples at the time of test. But in all cases he should also test a sample according to the standard procedure. The information he will derive from the standard test will be of help in forming his final decision.

That a stress concentration of considerably greater magnitude than any indicated by the authors does exist at the contact between tire and road surface cannot be doubted. The authors did not attempt to measure this stress. They got no closer to this contact area than the bottom of the 3-in. base course.

Admittedly it will be difficult to measure the stress at the point of contact. Possibly it can be accomplished through application of recently developed instruments of extreme sensitivity.

The writer's crude attempt to evaluate the pressure at the contact surface is not original. Recently he had occasion to review Westergaard's "Stresses In Concrete Pavements Computed By Theoretical Analysis" (*Public Roads*, Vol. 7, No. 2, April 1926). It appears that there are difficulties in the way of determining just how much to round off the peaks in the bending moment diagrams. Westergaard went at it this way (Page 32, *Public Roads* cited): "It is expedient to express the results of the special theory in terms of the ordinary theory in the following manner: Let the load, P, be distributed uniformly over the area of the small circle with radius a. The tensile stress produced by this load at the bottom of the slab under the center of the circle is denoted by σ_i. This stress is the critical stress except when the radius, a, is so small that some of the vertical stresses near the top become more important; the latter exception need not be considered, however, in case of a wheel load which is applied through a rubber tire. By use of the ordinary theory one may find the same stress at the same place by assuming the load to be distributed over the area of a circle with the same center, but with the radius b. One finds that this equivalent radius, b, can be expressed with satisfactory approximation in terms of the true radius, a, and the thickness, h, only."

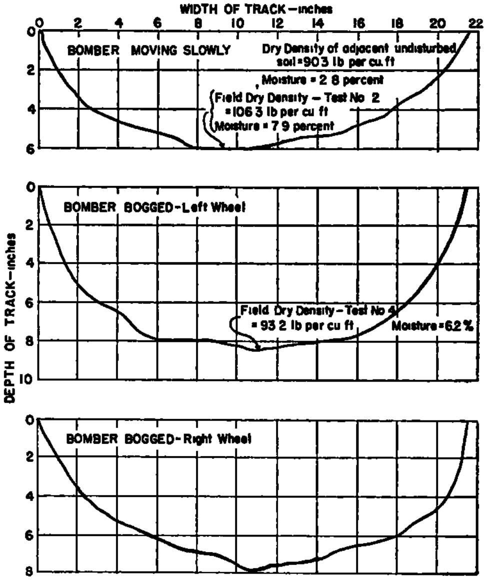

Figure 3. Tire Prints of a B-24 Bomber Made in an Emergency Landing on a CAA Airport 2½ Mi. East of Engle, New Mex. The field was constructed by leveling off topsoil with bulldozers and blades. The maximum cut and fill was about 8 in. and the topsoil forms the present surface of the field. The topsoil has the following characteristics: CBR at 0.1-in. penetration, compacted and soaked = 21.7. Optimum Moisture (Calif. static method) = 9.5%. Max. Dry Density (Calif. static method) = 115.0 lb. per cu. ft. Penetration Resistance, Proctor 1/20-sq. in. needle in compacted and soaked specimen = 2500 lb. per sq. in.

$$\frac{\text{C B R}}{\text{Proctor Needle Resistance}} = 0.087$$

Sieve No.	Percent Passing
20	100
40	95
60	77
140	36
200	28

Plastic Index—Nonplastic
Classification: Cassagrande SF
PRA A-2-F
Proposed PRA A-2-a
Density: Undisturbed topsoil = 90.3 lb. per cu. ft.
At Wedge Point of Print (bomber bogged) = 93.2 lb. per cu. ft.
At Wedge Point of Print (bomber moving slowly) = 106.3 lb. per cu. ft.

The writer ventures to suggest that "some of the vertical stresses near the top" are responsible for the grooving effect produced by pneumatic tires in asphalt surfaces.

The print of a bomber tire in desert soil is shown in Figure 3. The pressure concentration under the approximate center of the tire is well defined.

As the plane advanced into looser sand, perimeter shear came into play. In this loose cohesionless material the instrument of destruction was shortly brought to a halt.

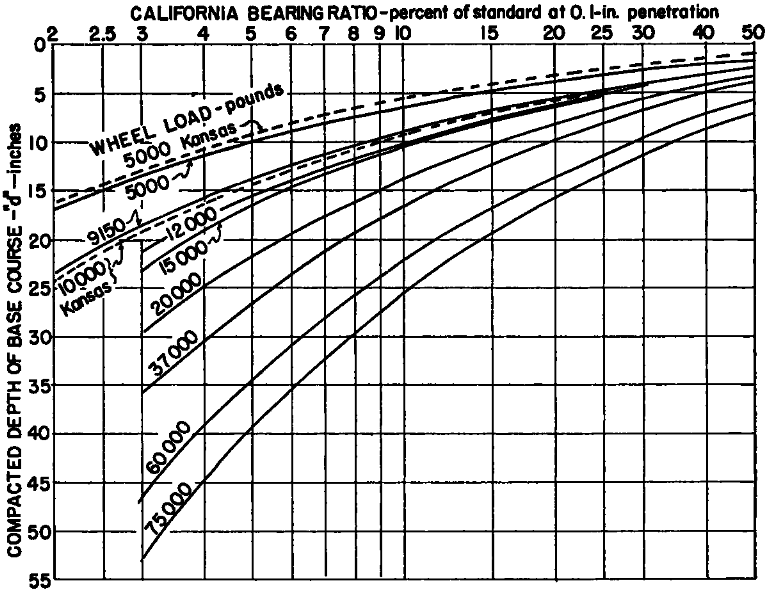

Figure 4. New Mexico Thickness Chart—Curves derived from circles of maximum pressure band on Professor Spangler's pressure diagrams where

$$d = 1.216 \sqrt{\frac{W}{s}} - 0.272\sqrt{A} \quad \text{(see Fig. 2)}$$

Tire Type	Wheel load	Contact area
Truck	5,000[a]	111.0
"	5,000	73.5
"	9,150	97.5
"	10,000[a]	111.0
"	12,000	130.0
Plane	15,000	273
"	25,000	417
"	37,000	570
"	60,000	800
"	75,000	800

[a] **Kansas Triaxial Shear Method where Contact Area** $= \dfrac{\textbf{W}}{\textbf{Tire Inflation Pressure}}$

COMPARISON OF BASE COURSE THICKNESSES REQUIRED BY (1) NEW MEXICO HIGHWAY DEPARTMENT CHART AND (2) CURVES COMPUTED FROM EQUATION

$$d = 1.216 \sqrt{\frac{W}{S}} - 0.272\sqrt{A}$$

It appears that several state highway departments make use of charts, graphs, or tables of some sort for quick reference in estimating thickness of base course over varying soils in subgrades.

New Mexico has used such a chart for the past six years. We have modified it from time to time. These modifications have been made after comparison with results of the CBR test.

In Figure 4 the New Mexico Chart is shown. Base course thicknesses for heavy traffic roads are shown as compacted depths, and, immediately below, is shown the approximate CBR of the subgrade material over which the given compacted thickness of base course is required.

It will be observed that our base course is made up of two courses of granular material; the upper course is of 3-in. compacted thickness and is used to level off irregularities in the lower, or ballast, course.

Also shown in Figure 4 are the curves computed from the writer's equation, and two curves (5000- and 10,0C0-lb. wheel loads) showing the value of d by the Kansas triaxial shear method.

The maximum legal wheel load under New Mexico Statutes is 9000 lb. The U. S. Army Training School Manual published by B. F. Goodrich rates a 9150-lb. load as requiring a 14.00–24 tire with a gross contact area, A, of 97.5 sq. in., at 90-lb. inflation pressure; this is the regular commercial type for use on paved surfaces. This size is the nearest to our legal load limit for which all data was given and 97.5 sq. in. is used as the value of A in computing the 9150-lb. curve.

A reasonably good agreement is shown between the 9150-lb. curve and the chart thicknesses. A tabular guide for depth of ballast and base predicated on grading and soil characteristics showing New Mexico highway practice is given in Table 2.

In closing the writer would call attention to the desirability of setting up a standard for arriving at the gross contact area for each wheel load. Texas and Kansas arrive at the gross contact area, A, by dividing the wheel load by the inflation pressure. Thus for a 9000-lb. wheel load and 90-lb. inflation these states arrive at a value for A of 100 sq. in. Texas uses this A as the top of the frustrum of their cone of pressure distribution. The radius of this area, A is 5.64 in. The U. S. Training School Manual gives the gross contact area for the recommended tire to carry a 9150-lb. load as 97.5 sq. in. The radius of this area, assumed circular, is 5.5 in., and there would be no practical difference in the thickness determined by the Texas method whether they use $W \div$ inflation pressure or The Training School area of 97.5.

However, Texas assumes the cone of pressure spreading downward from the periphery of a circle having an area $= W \div$ inflation pressure at an angle of 26½ deg., whereas, the writer's method assumes the cone of pressure spreading downward from the periphery of a circle whose area is 5 percent of $W \div$ inflation pressure at an angle of 24 deg. 54 min.

TABLE 2
NEW MEXICO STATE HIGHWAY DEPARTMENT
GUIDE FOR DEPTH OF BALLAST & BASE
(Argument-Grading & Soil Characteristics)

Type Percent Passing	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1" sq opening	100													
#4 U. S sieve	40–80	95–	Not significant											
#10 U S sieve	30–60	80–												
#40 U S. sieve	15–35	50–	65–	70–										
#200 U S sieve	5–15	20–	25–	25–	35–	35–55	20–	50+	50–	60–	35–	35+	35–	35+
Liquid Limit	25–	35–	30–	30–	35–	25–	40–	30–	30–	40–	40–	50–	50–	50+
Plastic Range	6–	6–	6–	8–	10–	6–	15–	8–	10–	12–	20–	20–	30+	20+
Dust Ratio	50–	50–												
(Comp Thickness)	0"	3"	5"	6"	8"	8"	9"	11"	11"	12"	14"	15"	17"	18"
Average California Bearing Ratio	80–100	50–100	30–50	20	12+	12+	10	7–8	7–8	6	5	4–4.5	3.5	3
Utility	leveling	Ballast		Subgrade Reinforcement				Embankment				Unsatisfactory (Waste)		

Soil falling in columns Nos 12, 13, and 14 should be used in subgrade only when better material is not available within an economical haul

PI to nearest 0 5% Grading to nearest 5% Except columns 1 & 2

Texas sets up certain criteria for the value of S which are not unlike the elements of the New Mexico Chart.

COMPARISON OF THE VALUES FOR d AND THE CBR CURVES

The CBR Curves as shown in the U. S. Training Manual 5-255, Page 63, do not include a 9000-lb. wheel load. They do show a curve for a 12,000-lb. load. It is the writer's understanding the tire gross contact area for this load is 130 sq. in.; the writer's thickness curve for this load is based on 130 sq. in. For a CBR of 3 the California curves call for a

"Combined Thickness of Pavement and Base" of 22½ in. The writer's method calls for a thickness of 21 in. for base only. As the bearing ratio increases the difference between the respective values of d decreases. At a bearing ratio of 20 the values are identical.

The writer does not know the method used in computing the CBR Curves. Dr. McLeod's formula for these curves, (see Journal of Asphalt Technology, March–June, 1943, Page 7) is $t = \frac{r}{S^n}\sqrt{\frac{P}{S}}$ ($n = 0.43$ when $S = 3$). The writer has been unable to find close agreement between this formula and the California curves when using commonly accepted contact areas. For example: Using a 12,000-lb. wheel load and a CBR of 3, McLeod's formula becomes $22.5 = \frac{r}{3^{0.43}}\sqrt{\frac{12{,}000}{30}}$; then $v = 4.86$, and contact area = 74.45 sq. in. This is the contact area required to satisfy the conditions of the formula since the California Curve for $P = 12{,}000$ lb. and CBR = 3 provides a thickness of 22.5 in.

Goldbeck rates the contact area of a tire under a 12,000-lb. load as 130 sq. in. The writer has used this area in his method and arrives at a thickness of 21 in.

It is possible that McLeod uses the net contact area. This factor needs clarification.

SUMMARY

The method described herein is an attempt to evaluate the concentrated pressure under a pneumatic tire at the contact of tire and base course, and to estimate the required thickness of base course necessary to reduce the unit pressure to a value not in excess of the subgrade bearing value.

DISCUSSION

W. H. Campen, *Omaha Testing Laboratory*. I believe that three of the assumptions used in developing this formula are erroneous. First the CBR value obtained on subgrade soils do not represent actual load bearing values. Rather they are bearing indices. Those who derived the CBR load-thickness curves correlated CBR subgrade values with load, superimposed thickness, and performance.

Secondly it is absolutely incorrect to assume that equal thicknesses of all compacted bases have the same distributive power. It is known that the distributive power of bases depends not only on thicknesses but also on mechanical gradation, shape of aggregate particles, degree of densification, and moisture content. Mr. A. T. Goldbeck[1] recognizes the effects of these conditions when he introduces the factor k in his formula for determining thickness. Our own tests[2] reported in 1945 show the effect of degree of densification on the bearing index of base mixtures.

In addition to the thickness and quality of the base there is another very important factor which affects the distributive power of the base; that is the behavior of the subgrade itself. Our field work on subgrades and layered systems[3] shows that the load bearing value increase due to superimposed layers varies with some inherent properties of the subgrade. For instance· the rate of increase with an 800-sq. in. plate varied from 0.8 to 4.0 psi. per in. of thickness. L. A. Palmer and James B. Thompson in a paper presented at this meeting show that with a base thickness of 8 to 9 in. the strength imparting power varies from 1.4 to 3.8 psi. per in. of thickness as the subgrade load bearing value increases from 10 to 100 psi.

E. B. Bail, *closure*. The writer agrees with Mr. Campen that the CBR values are bearing indices. They are a measure of the soil's resistance to displacement and, as such, they measure the load bearing value.

The gradation of the gravel base courses used in the Spangler and Ustrud experiments is quite similar to the specification grading of most of the highway and airport bases constructed in the United States. It is believed, therefore, that the proposed method would have quite general application.

[1] *Proceedings*, Highway Research Board Vol. 20 (1940).

[2] *Proceedings*, Highway Research Board Vol. 25 (1945).

[3] *Proceedings*, Highway Research Board Vol. 24 (1944).

The value d is the compacted thickness. Compaction is pretty well standardized at around 95 percent Modified AASHO for Airports and 90 to 95 percent Proctor for highways. It did not occur to the writer to elaborate as to the degree of compaction.

There is as yet no definite evidence that mechanical gradation or shape of aggregate particules influence the distributive power of bases. McLeod[4] found "There is no positive evidence that for similar conditions of density and moisture content, all other factors being equal, that any one type of granular base course material has a greater supporting value per unit of thickness than any other type." Dr. McLeod's observations fairly describe our own experience with granular bases.

This factor has long since been recognized in highway construction. It is common practice to improve subgrade bearing value by cross-haul or by importing selected borrow. The proposed formula is of value in determining the bearing power of the subgrade and indicating to what depth this reinforcement should be extended.

[4] Norman W. McLeod "Airport Runway Evaluation in Canada," Res. Rept. 4-B, Highway Research Board (1947), p. 24, 39, 62.

FLEXIBLE PAVEMENTS—DESIGN AND SELECTION OF MATERIALS

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SYNOPSIS

Until recently the Department of Main Roads, New South Wales, used the soils classification developed by the U. S. Public Roads Administration as published in *Public Roads* magazine, February 1942.

Some soils of considerable importance in New South Wales, however, did not fit precisely in this classification; consequently a new system of numerical interpretation based on other simple identification tests was developed locally and tentatively is in use.

This report covers the investigational work through which the new method and its applications evolved. Most of the work has been confined to the eastern half of New South Wales, 29 to 30 deg. South Latitude. Climate varies from wet on the coast to dry at the interior. Drainage is usually satisfactory with the ground water well below the subgrade.

Included in the investigation were: (1) determination of specification limits for surface course materials for use without bitumen; (2) specifications for material courses to receive light bituminous surface; (3) development of a numerical method for designing pavement thickness required over given subgrades or lower base courses.

Involved also were the development of an accelerated weathering test for shales for pavement construction or for the subgrade and a method for assessing quality of sandstones.

Study of traffic influences indicated that magnitude of load was more important than frequency of heavy load for determining if failure would occur. However, frequency of heavy loads influenced the time at which failure occurred. Load had noticeable effect on total pavement thickness, but small effect on the required thickness of surface course.

The design method is set out in two appendices to the report. The first treats the test procedures which follow the Public Roads Administration methods with certain exceptions as explained. The second appendix gives the numerical method of interpretation of test results, and applies two rules: (1) reduce to a single number the effect of departures from maximum density grading taking Wilhelm's exponential series for maximum density; and (2) adjust the variable to a point-score system for evaluation correlated with service.

It is concluded that the same rules and formulas could probably be safely used in other areas with similar climate and traffic